Faster, Better, Cheaper with Muon Colliders?

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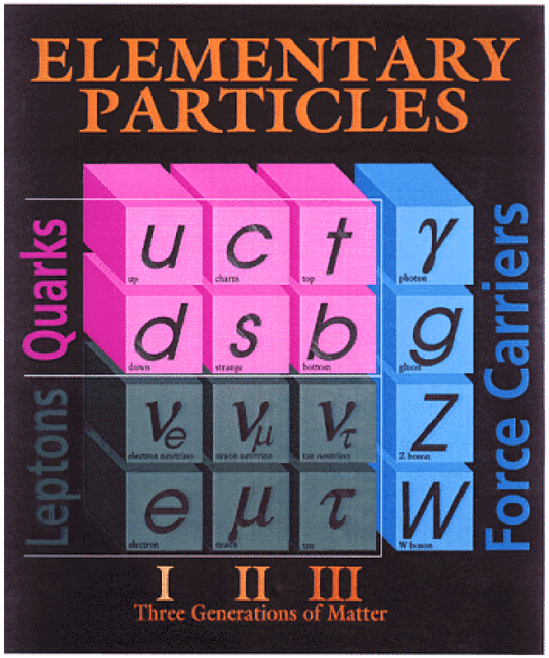
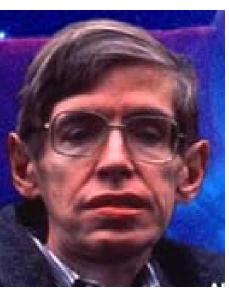
Topics:

- their promise for HEP
- main challenges: muon beam cooling, neutrino radiation, cost management
- illustrative straw-man scenario for rosy HEP future with muon colliders (& guess cost)
- conclusions

Quest to Understand the Philosophy of Nature



- "periodic table" of elementary particles with properties described by the "Standard Model"
- Standard Model is a stop-gap theory: incomplete & not self-consistent
- why does it exist? How does it fit into the existence & structure of the Universe?



Stephen Hawking (Cambridge U.): 50% chance we will reach a unified understanding of our physical Universe within the next 20 years.

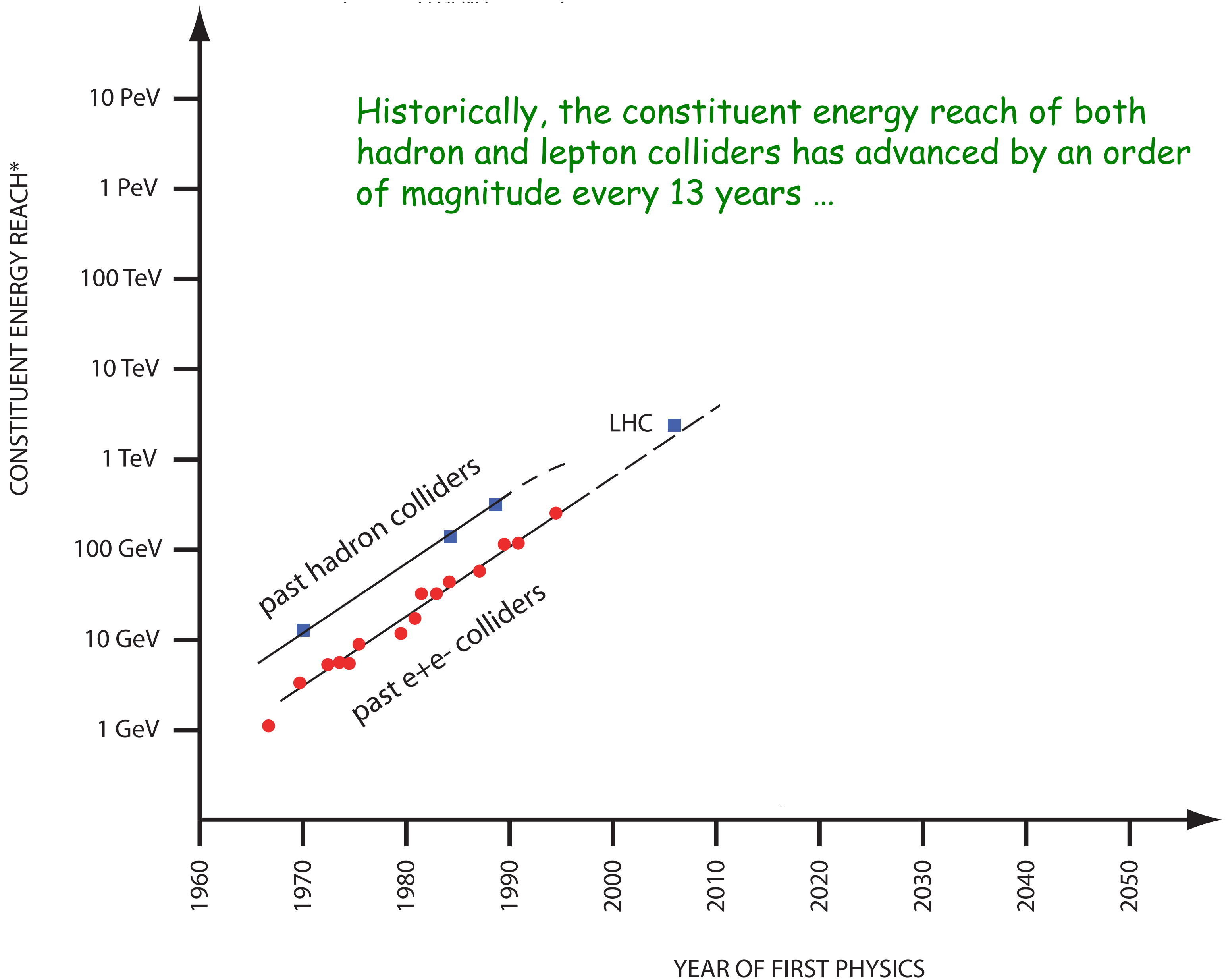
Alvaro de Rujula (CERN): Huh! No chance without further experimental information. (Probably the consensus opinion.)

Colliders that explore the energy frontier provide the most powerful & direct way to advance experimental HEP

$$E = mc^2$$

Center-of-mass energy of colliding point-like constituents to directly explore this mass scale

Livingston Plot for Collider Progress

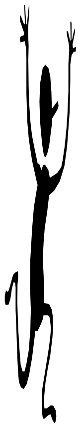


B. King; "Muon Colliders", Northwestern University, 10 December, 2001.

“We need revolutionary ideas in accelerator design more than we need theory. Most universities do not have an accelerator course. Without such a course, and an infusion of new ideas, the field will die.”

Samuel C. Ting, quoted in Scientific American, January, 1994.

WHY ADD MUON COLLIDERS?



Electrons
are too light

Discovery reach
of a few TeV ?

Protons are composite
& strongly interacting

Discovery reach of
some 10's of TeV ?

Add Muons,
though unstable

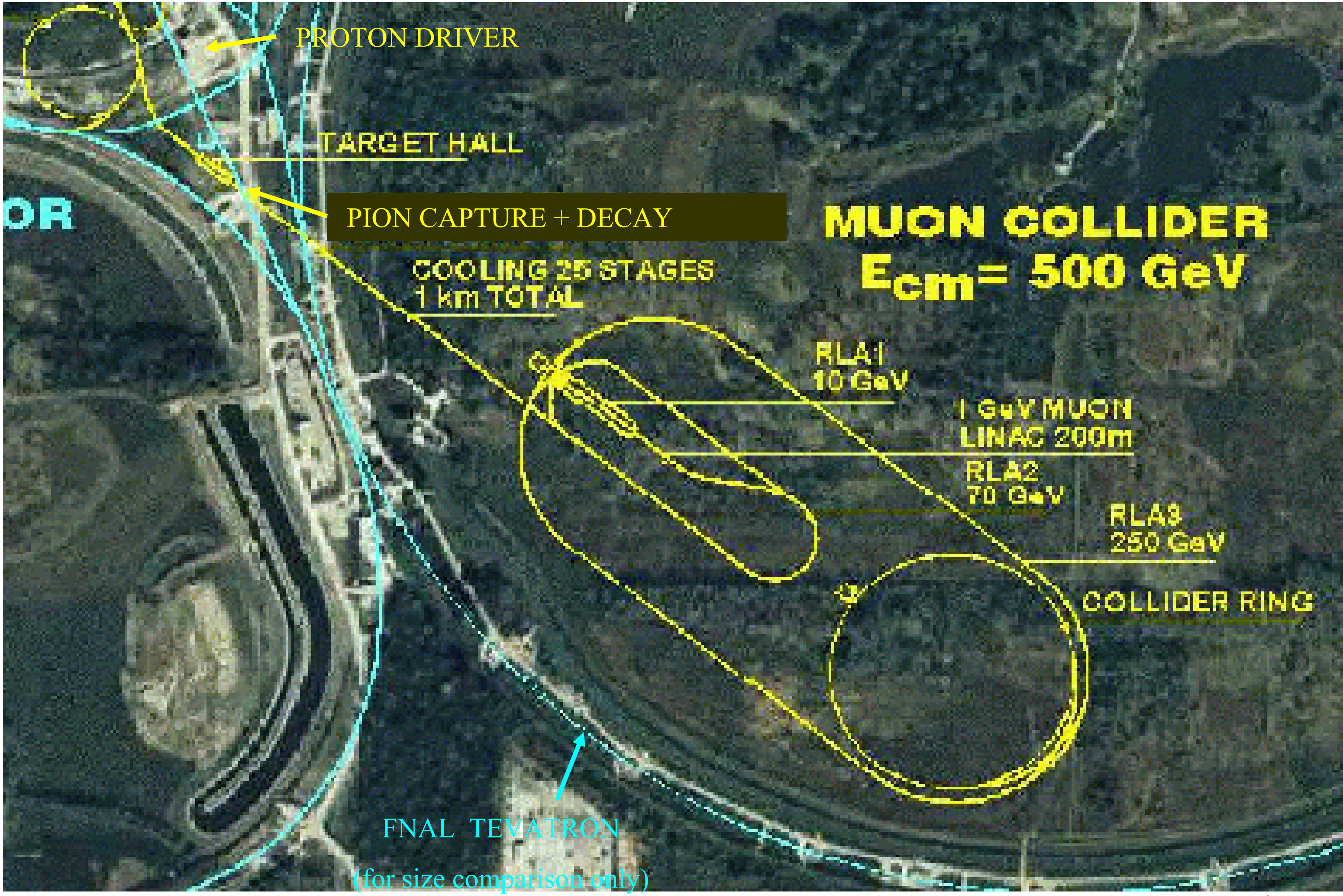
Discovery reach of
~100 TeV (circular)?
~1 PeV (linear)???

$m_\mu \sim 206 \times m_e$
$\sim m_p / 8.9$

$\mu \to e\nu\nu$ with
$\tau_\mu = 2.2\ \mu s$

Muons have the highest potential discovery reach of all collider projectiles, using clean lepton-lepton collisions.

Example Layout for a "Stand-Alone" Muon Collider

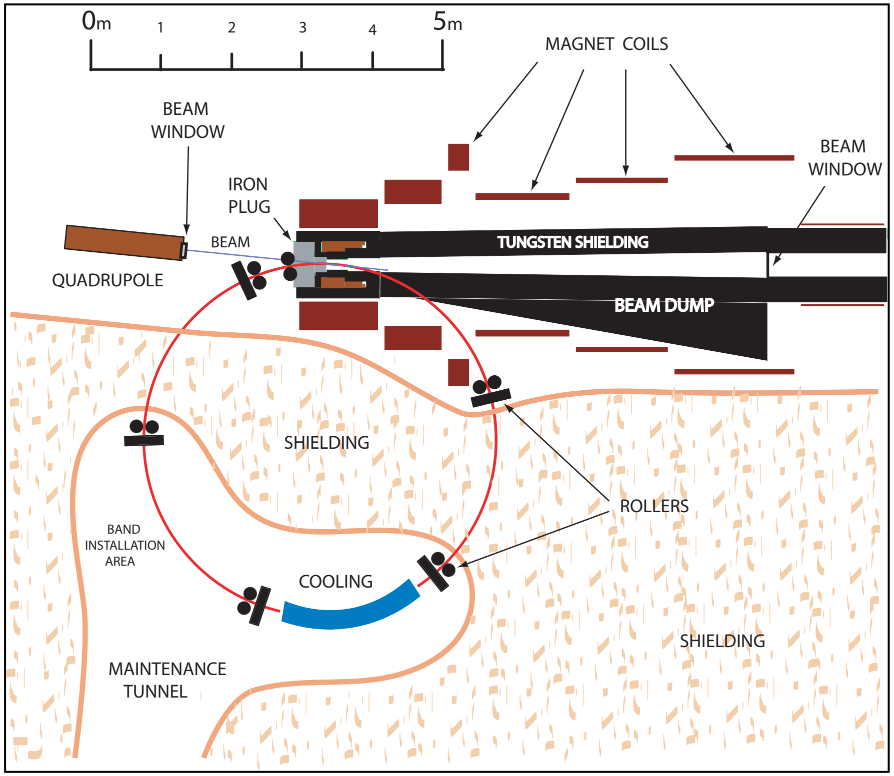


Source: Fermilab

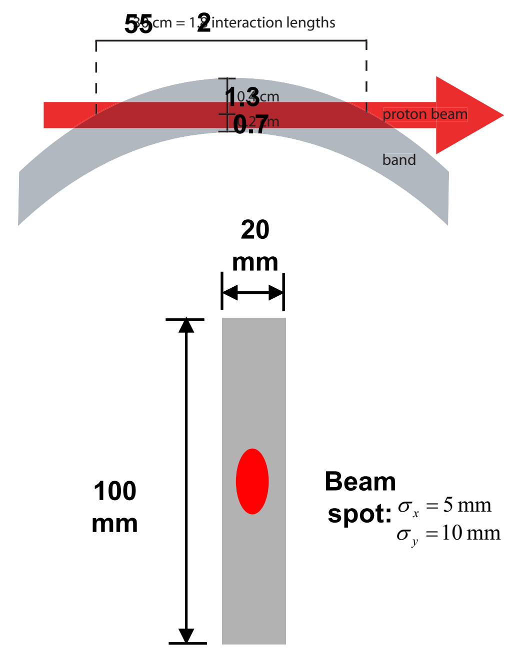
PION PRODUCTION TARGET

no longer the co-dominant technical challenge

Ref. BJK, Mokhov, Simos & Weggel, "A Rotating Metal Band Target for Pion Production at Muon Colliders", *Proc. 6-Month Study on HEMC's*, available on CD, Rinton Press.



Ti-alloy band



Can use large beam spot size on target to produce pion "cloud" => shock heating stresses can be managed.

Continuous rotation to new target material allows convenient cooling and dilutes the radiation damage. Such target designs can comfortably handle pulsed proton beams of several MW & ~100 kJ/pulse.

MUON BEAM COOLING

signature technology & dominant technical challenge

Luminosity & Beam Emittance

$$\text{Luminosity, } \mathbf{L} \sim \frac{\text{collision freq.} \times \mathrm{N}_{\text{bunch}}^2}{\text{spot size}} \sim \frac{\text{ave. beam current} \times \mathrm{N}_{\text{bunch}}}{(\Delta x.\Delta y)_{\text{IP}}}$$

~ "specific luminosity" – maximize this

A mathematically conserved quantity in any bulk EM fields (acceleration, focusing, bending) is the …

$$\text{Normalized 6-D emittance} = \text{rel. invariant phase space volume, } \varepsilon_{6\mathrm{N}} \equiv \prod_{i=x,y,z} \Delta p_i \Delta x_i$$

(& obvious generalization to include correlations)

$$= \varepsilon_{\text{long.,N}} \, . \, \Delta p_x . \Delta p_y \, . \, \Delta x . \Delta y$$

At collision …

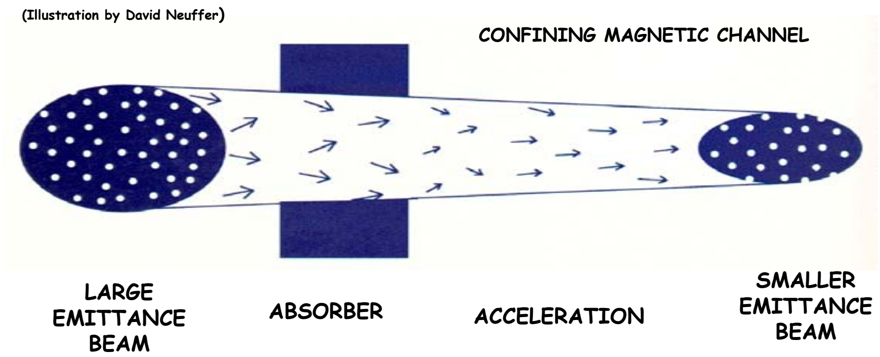
constrained by final focus design, etc.

helps determine spec. luminosity

$$\boxed{\text{Beam cooling} \equiv \text{increase in bunch brightness: } \frac{\mathrm{N}_{\text{bunch}}}{\varepsilon_{6N}}}$$

IONIZATION COOLING CHANNEL (1 of 2)

Simple concept for transverse cooling:

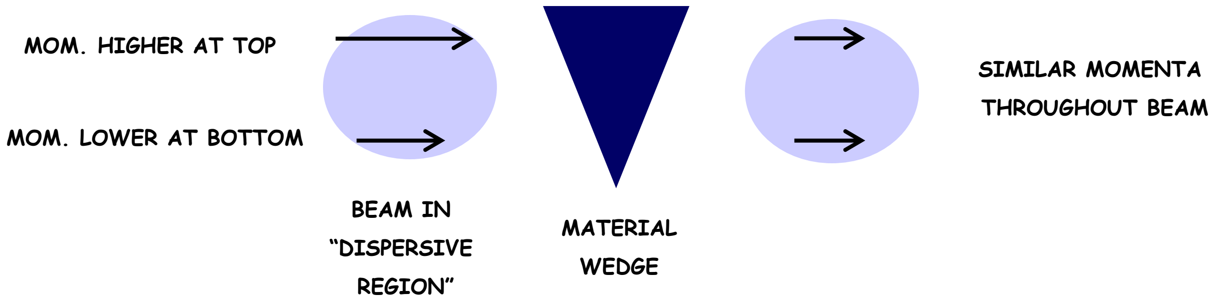


However, Coulomb scattering and energy straggling compete with cooling:

A) confines cooling to a difficult region of parameter space (low energy, large angular spreads)

B) need to control beam momentum spread to obtain large reduction (e.g. 10^6) required in 6-D phase space:

"emittance exchange" using wedge:



IONIZATION COOLING CHANNEL (2 of 2)

So far we have:

a) general theoretical scenarios & specs. to reach the desired 6-D emittances

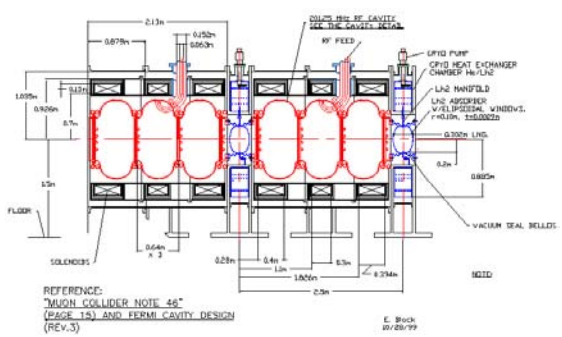
b) detailed particle-by-particle tracking codes (modified GEANT,ICOOL) & (new) higher order matrix tracking code (modified COSY-infinity) + (new) wake field code interface

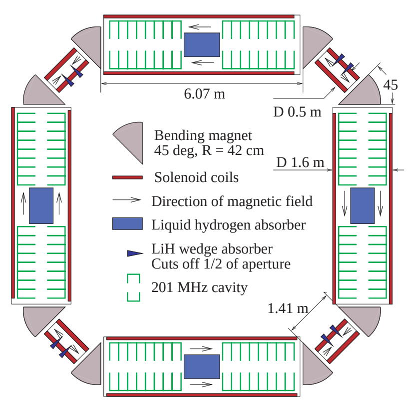
c) engineering designs of pieces

d) neutrino factory designs for first factor of ~10 *transverse* cooling

e) "ring cooler" design progressing for MUCOOL expt. with predicted full 6-D cooling by factor of ~32 (c.f. muon collider may need up to ~10^6 ~ 32^4)

2 sub-units of a cooling stage (Black, IIT)





"ring cooler"

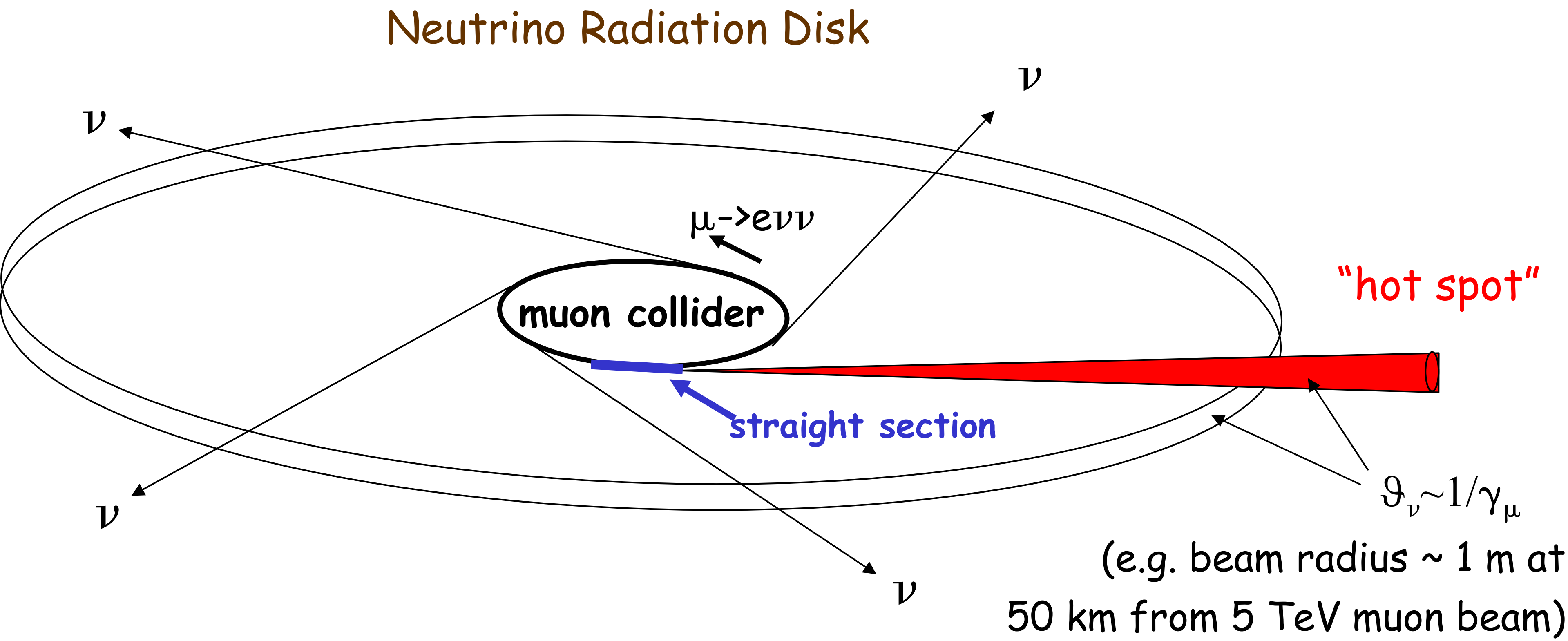
(Balbekov, FNAL)

But we have yet to put the pieces together to "build the muon collider cooling channel on a computer" and, thus, establish the likely feasibility of muon colliders.

Might we Make Even Cooler Muon Beams?

- ionization cooling has potential only for moderately cool beams: ϵ_{6N} ~10 orders of magnitude from intra-beam scattering limits
- most promising technology for a cooling "after-burner" is Optical Stochastic Cooling (OSC) (Mikhalichenko & Zolotorev, 1993)
- OSC is the optical analog of the established technology of microwave stochastic cooling
- OSC is still very speculative. However, there are proposals to experimentally test the concept using GeV-scale electron beams (easier/cheaper than with muons).

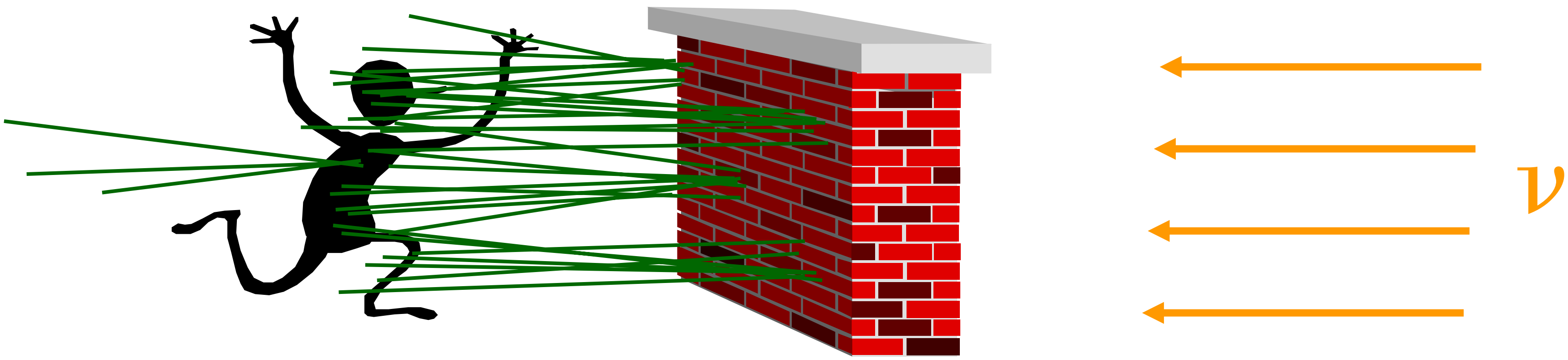
NEUTRINO RADIATION ISSUES



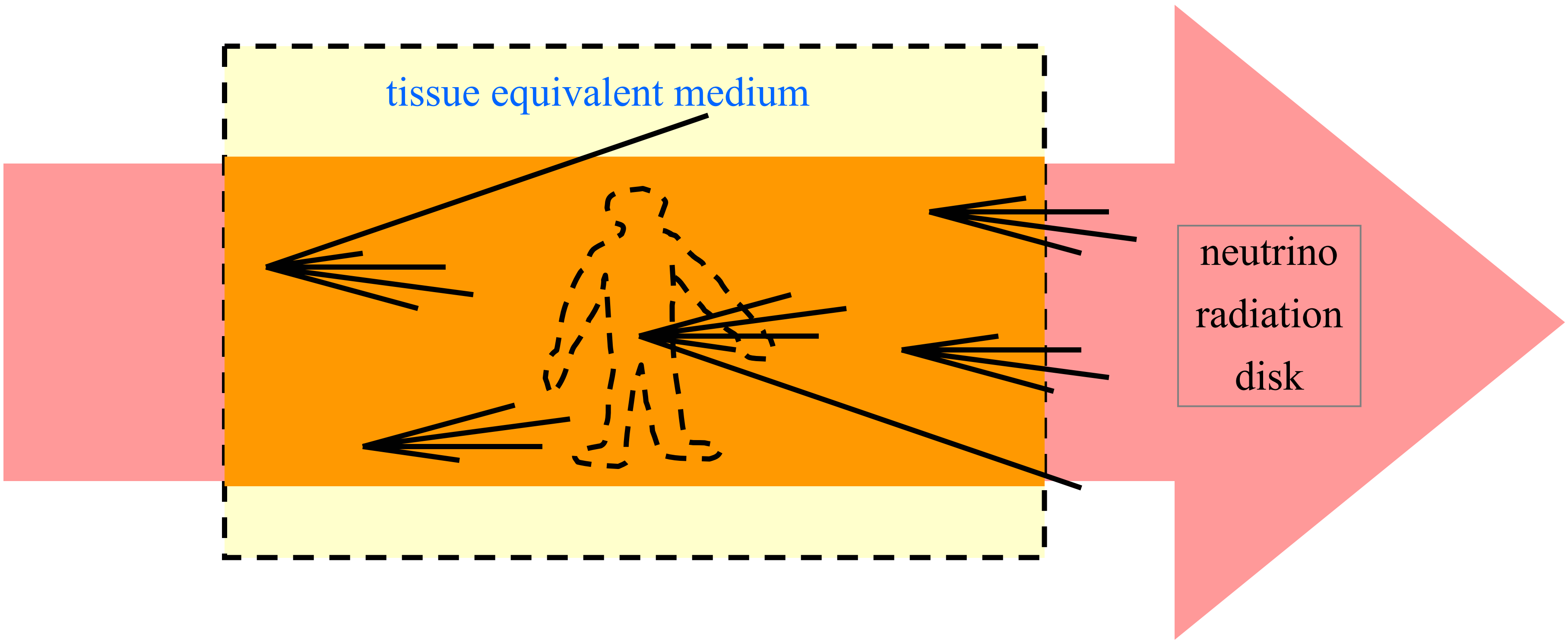
*ref. B.J. King, " Potential Hazards from Neutrino Radiation at Muon Colliders", physics/9908017;
B.J. King, "Neutrino Radiation Challenges and Proposed Solutions for Many-TeV Muon Colliders", Proc. HEMC'99, hep-ex/0005006.

THE OFF-SITE RADIATION CONSTRAINT

Neutrino interactions in the surroundings initiate the charged particle showers that lead to the radiation constraint ...



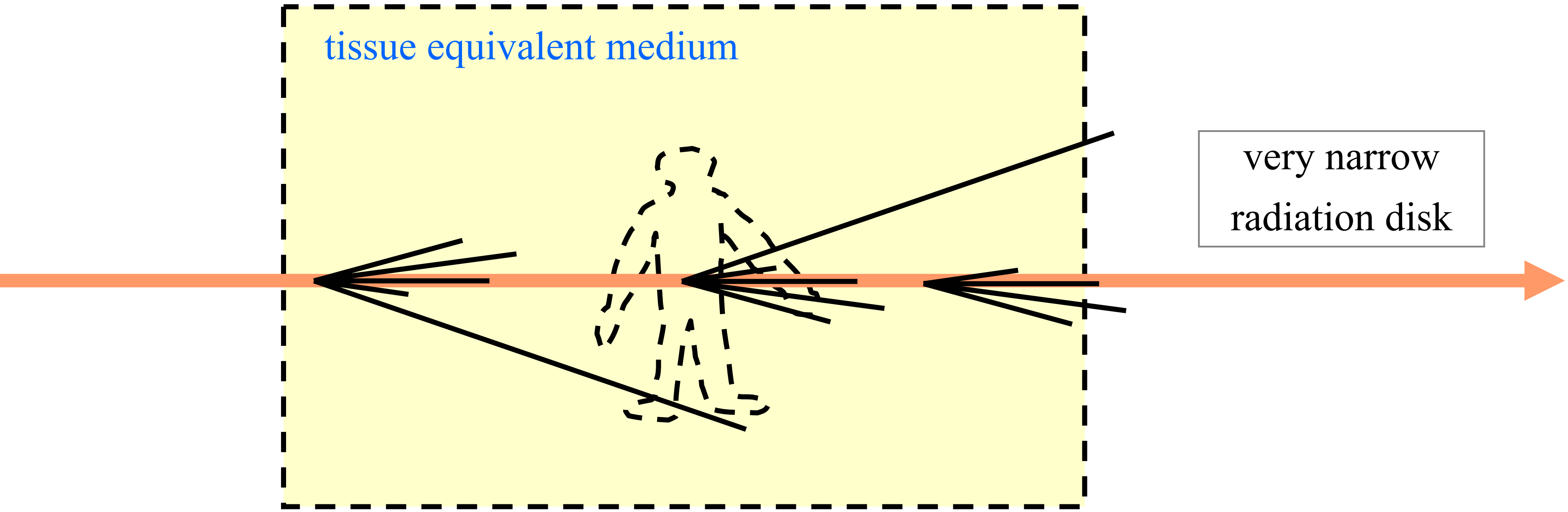
"Equilibrium Approximation" for Dose Calculation



Max. dose absorbed = energy of neutrino interactions in person

N.B. breaks down close-by & at many-TeV energies (next slide)

1) equilibrium approximation breaks down:



2) neutrino cross-section levels off:

$$\frac{\left(\frac{\sigma_\nu}{E_\nu}\right)_{E=100\,\mathrm{TeV}}}{\left(\frac{\sigma_\nu}{E_\nu}\right)_{E=1\,\mathrm{TeV}}} = 0.33$$

Predicted Neutrino Radiation Dose up to ~TeV Energies*

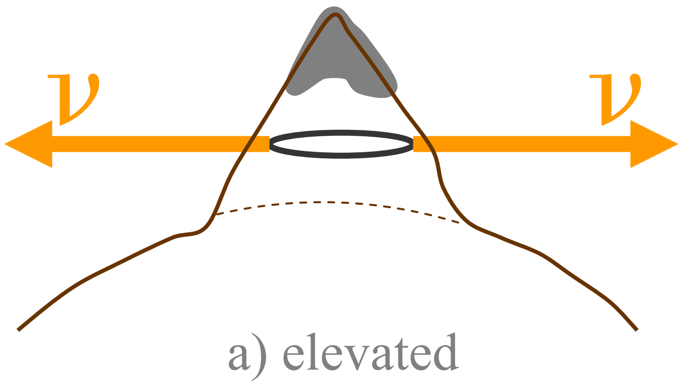
$$\text{Radiation Dose[mSv]} \cong 0.4 \times N_{\mu^+}[10^{20}] \times \left(\frac{\text{length of str. section}}{\text{collider depth}} \right) \times \left(E_{\text{CoM}}[\text{TeV}] \right)^3$$

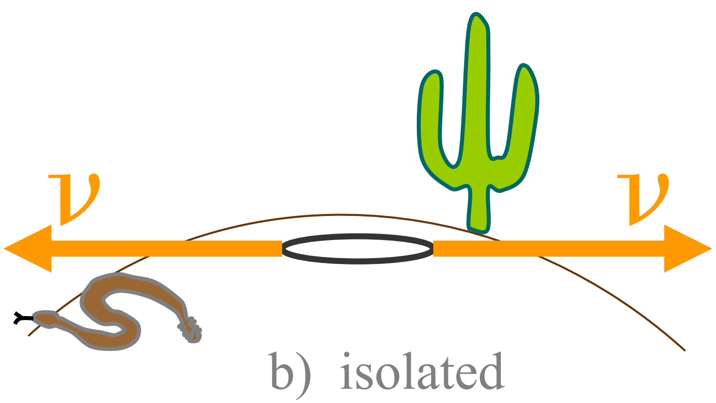
- 1 mSv/yr = U.S. Federal off-site limit ~ natural background
- a conservative, <u>worst-case</u> order-of-magnitude analytic calculation
- collider depth ~ (distance to surface)^2 for a non-tilted ring and locally spherical Earth
- the formula overestimates the dose close-by and at many-TeV energies
- low beam currents allow very low radiation doses

muon collider specs. to follow will have in-plane ave. dose < 10^{-3} mSv/year, straight section dose <~ 10^{-2} mSv/year

*ref. BJK, "Neutrino Radiation Hazards at Muon Colliders", physics/990817

Ultimate Energies together with Ultimate Luminosities => Special Site

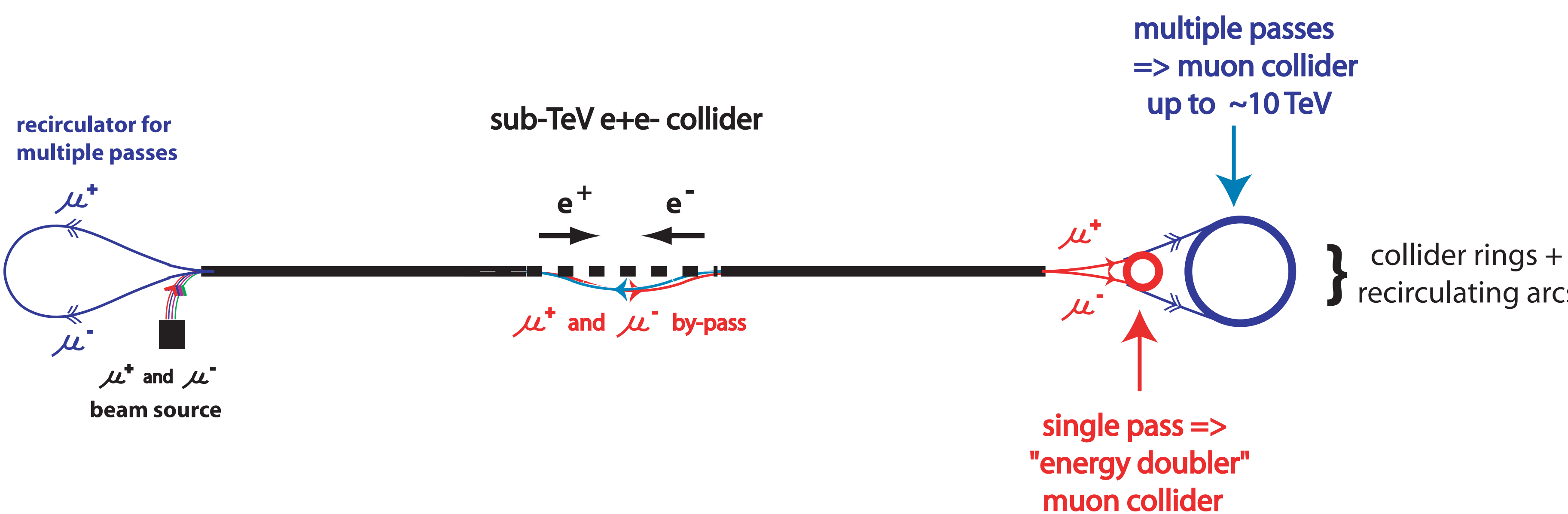




POTENTIAL SYMBIOSES WITH e+e- & HADRON COLLIDERS

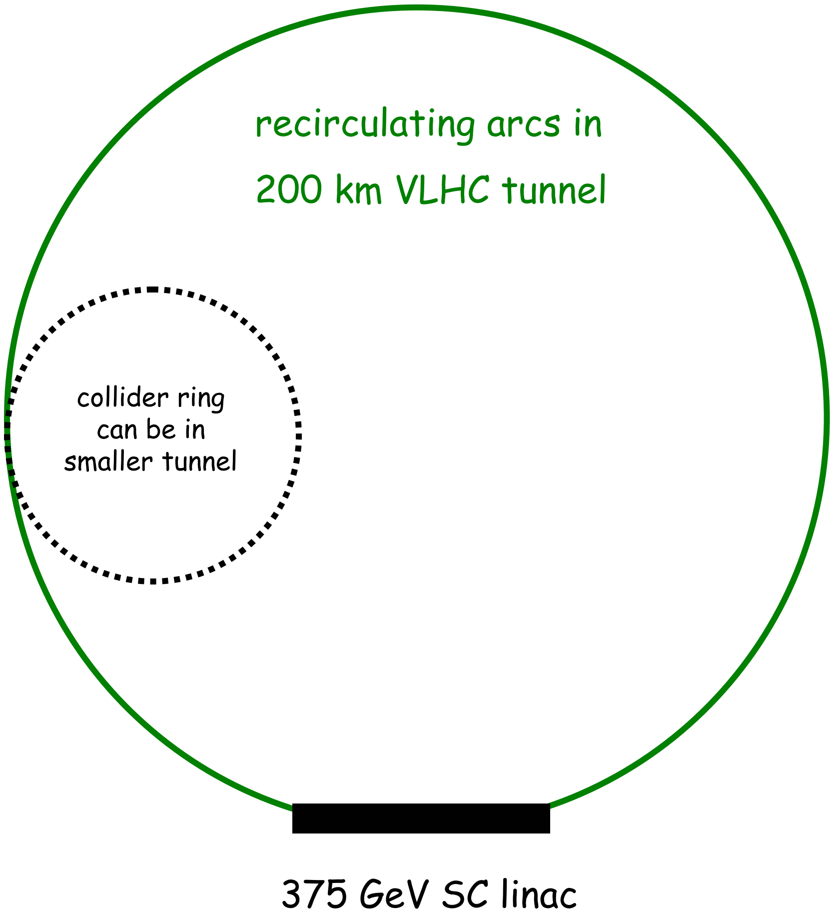
Mu-LCs to ~10 TeV

- mu-LCs = accelerate muons for muon collider in linacs of e+e- collider as an energy upgrade
- concept presented in Proc. Snowmass'96 in "An Energy Upgrade from TESLA to a High-Energy Muon Collider", D. Neuffer, H. Edwards and D. Finley; re-examined in Snowmass 2001 linear collider session



ACCELERATION OPTION TO MANY TEV

e+e- collider linacs as the acceleration driver & recirculate in a BIG tunnel



- cost saving by multiple passes through single magnetic channel, using either large acceptance lattice (“FFAG”) or fast-ramping magnets
- require average accelerating gradient >> $m_\mu c/\tau_\mu$ = 0.16 MeV/m :

$$\frac{375\,\mathrm{GeV}}{200\,\mathrm{km}} = 1.88\,\mathrm{MeV/m}$$

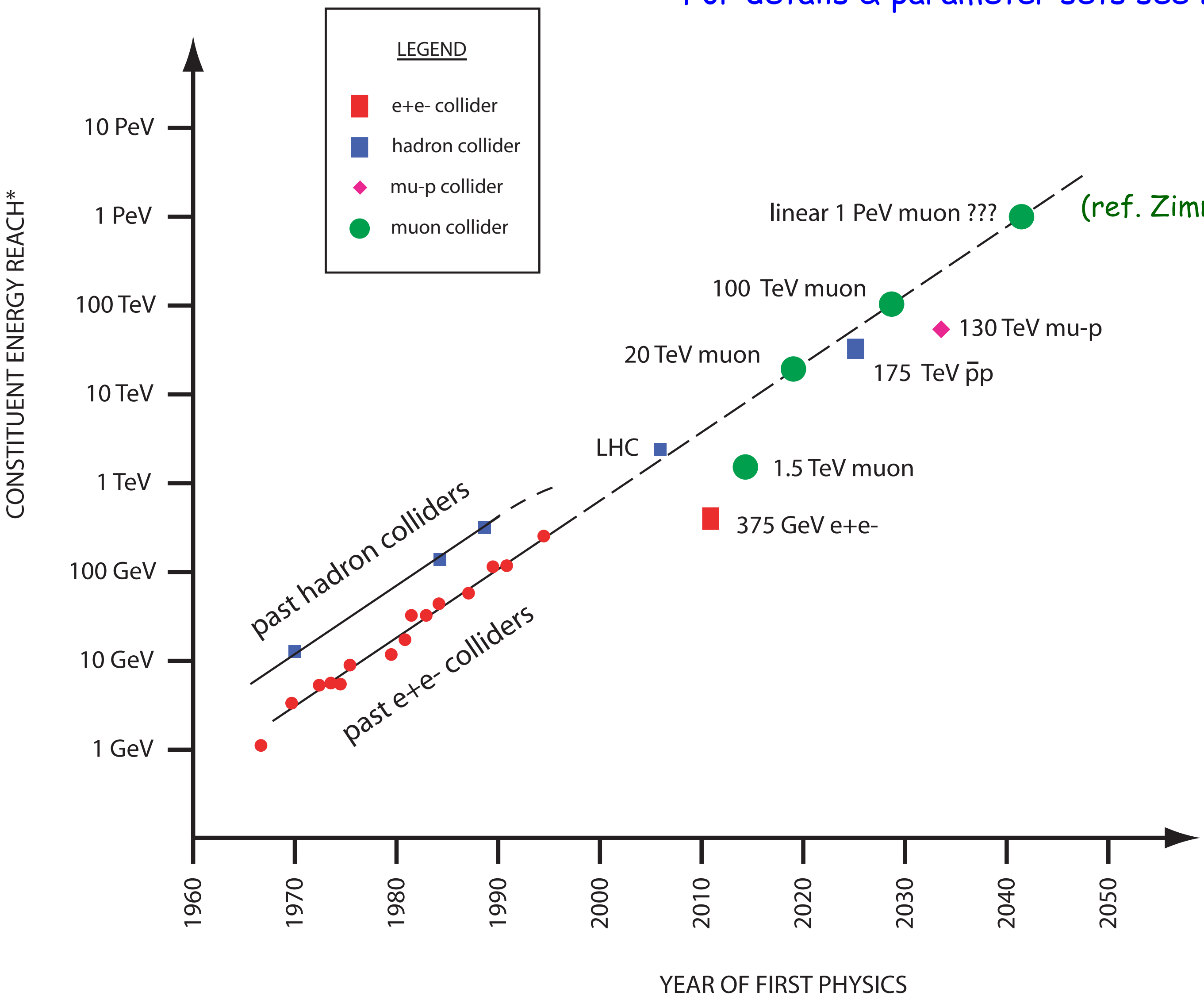
"STRAW-MAN" SCENARIO

for holding to the historical rate of progress in energy frontier colliders

CAVEAT EMPTOR: illustrative only. The R&D assumptions on technologies and cost savings may or may not turn out to be realizable in practice. How feasible/optimal or otherwise any such scenario is depends on current and future HEP & R&D results.

THE SCENARIO ...

For details & parameter sets see BJK paper in preparation.

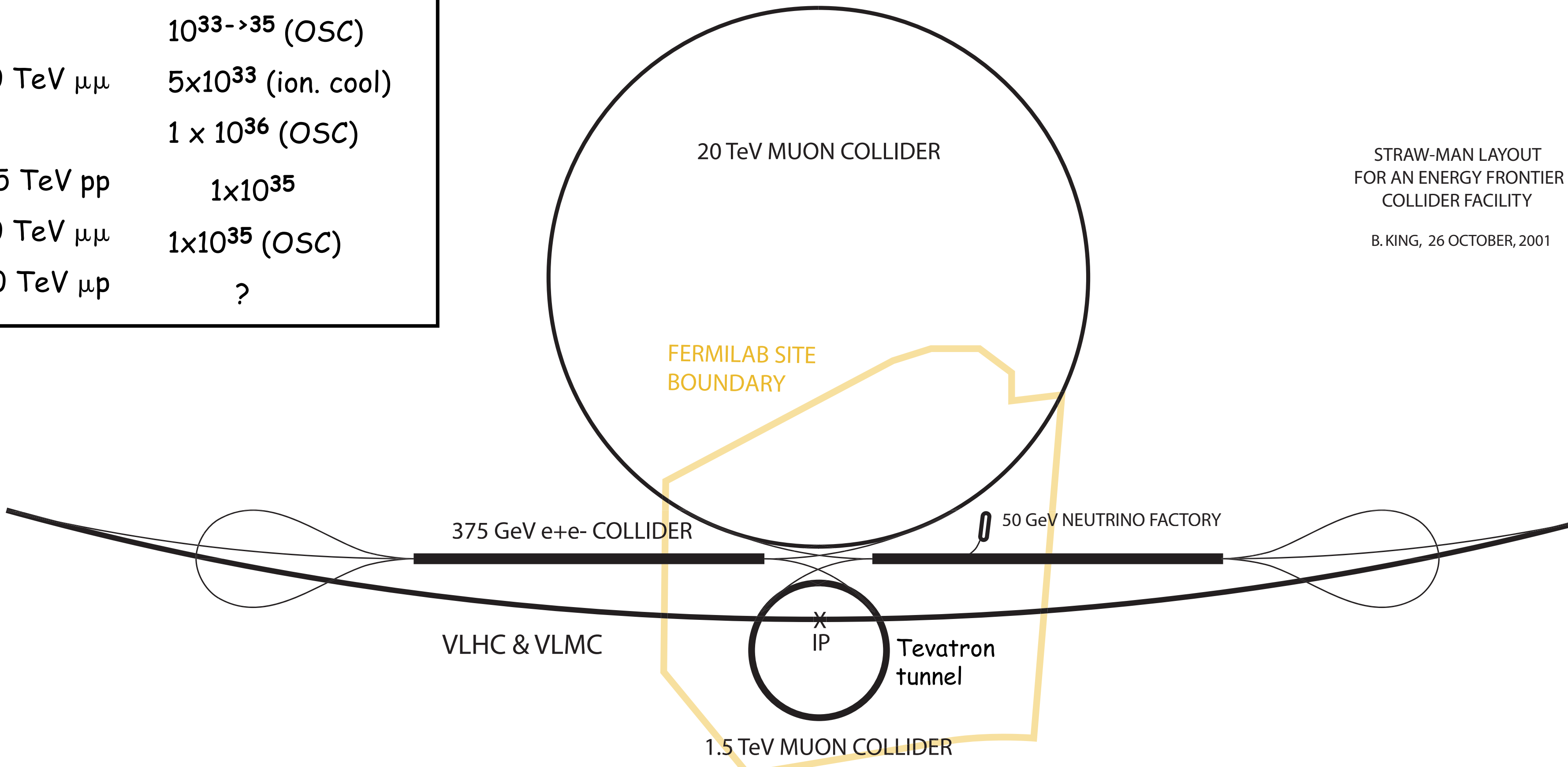


* assume constituent energy reach for hadrons = 1/6 x CoM energy

B. King; "Muon Colliders", Northwestern University, 10 December, 2001.

FACILITY AT FERMILAB (OR CERN?)

Collider	L [$cm^{-2}.s^{-1}$]
375 GeV e+e-	1×10^{34}
1.5 TeV $\mu\mu$	10^{33} (ion. cool)
	$10^{33->35}$ (OSC)
20 TeV $\mu\mu$	5×10^{33} (ion. cool)
	1×10^{36} (OSC)
175 TeV pp	1×10^{35}
100 TeV $\mu\mu$	1×10^{35} (OSC)
130 TeV μp	?



FACILITY AT DESY

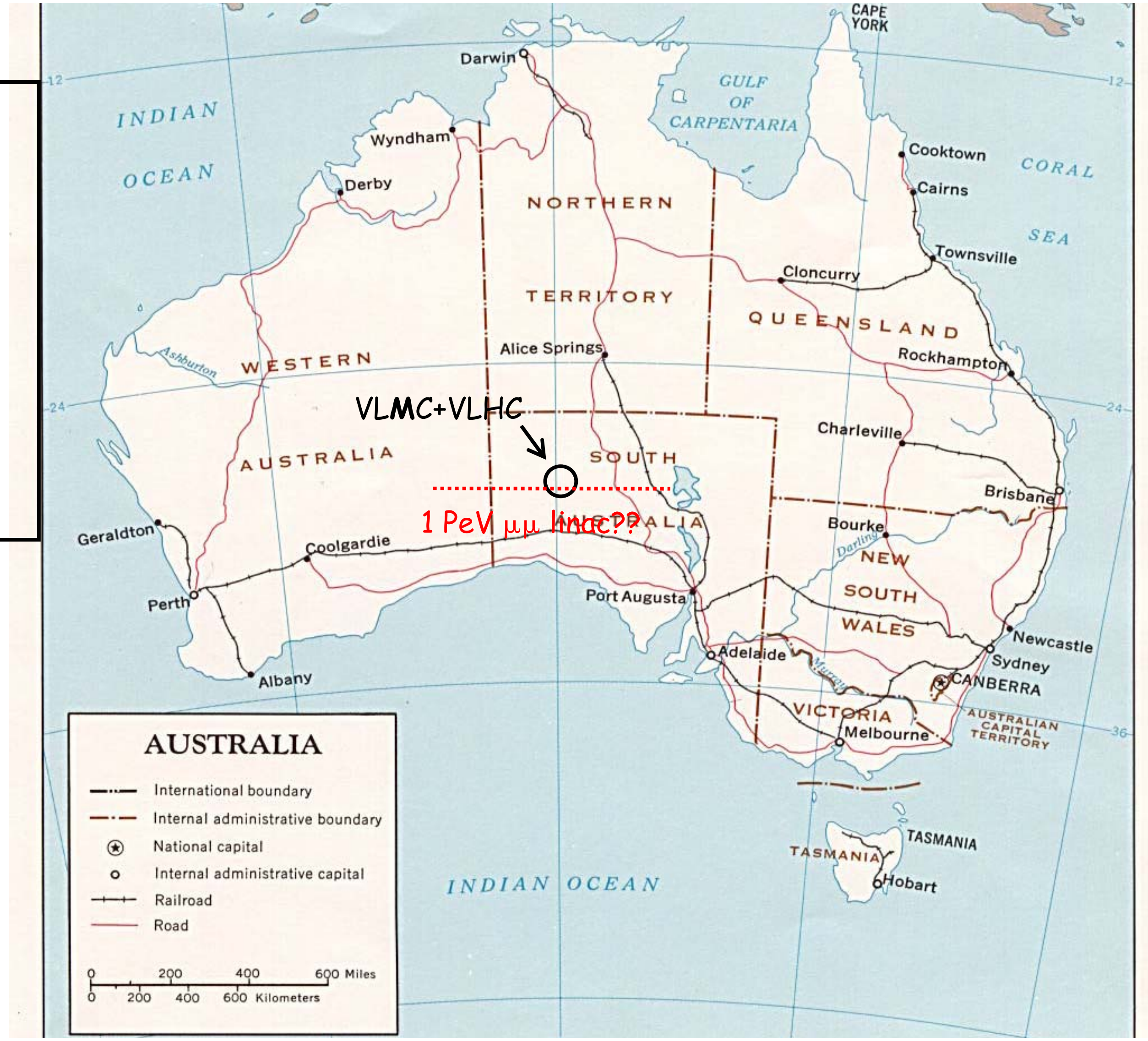
Collider	L [$cm^{-2}.s^{-1}$]
500-800 GeV e+e-	few x 10^{34}
2 TeV $\mu\mu$	1×10^{33} (ion. cool) 3×10^{34} (OSC)
3.2 TeV $\mu\mu$	1×10^{33} (ion. cool) 8×10^{34} (OSC)

TESLA linac

HERA tunnel

ISOLATED "NEUTRAL" WORLD LAB.

Collider	L [$cm^{-2}.s^{-1}$]
20 TeV μμ	1×10^{36} (ion. cool)
175 TeV pp	1×10^{35}
100 TeV μμ	1×10^{36} (ion. cool)
	5×10^{37} (OSC)
130 TeV μp	?
1000 TeV linear μμ	5×10^{35} (OSC, Zimmermann para.)



That would be fantastic!

But how could we ever afford it?

Magnet Costs: The Dominant Financial Challenge

Slides from Mike Harrison (BNL)

"Magnet Challenges: Technology and Affordability"

HEMC'99 Workshop,

Montauk, NY, Sept'99

Affordability

Caveat: collider ring only; acceleration may be more expensive..

- RHIC Dipoles 8cm, 10m, 4T, FY95 cost $110K each
- HEMC Dipole
  - 8cm -> 15cm 50%
  - 4T -> 7T 50%
  - 10m -> 15m 40%
  - FY95 -> FY00 15%
  - Estimate HEMC Dipole $400K or $26K/m based on RHIC
- 10 Tev needs 15km circumference -> magnet costs ~$400M. Ring costs = dipoles x 3(or4) = $1.2(6)B (probably a lower bound since HEMC dipoles are more complex than RHIC)

Encouraging

Conclusions

- A 10 Tev machine based on Nb-Ti magnets (7T dipole) is challenging but possible
- A 100 Tev machine does not look feasible based on 10T cosine theta dipoles
- A different magnet design (no mid plane cryogenics) would help
- Newer technologies (Nb3Sn, HTS) would be beneficial assuming that costs are reasonable and they work

work in progress for neutrino factory;

not relevant for low current colliders

Guess at Costs

(Draft table from BJK paper in preparation.)

Table 1: Subsystems for the colliders in the scenario up to the year 2034. An \X" marks the colliders using the subsystem. A guess at the relativ e cost of the subsystems is given, in arbitrary units.

subsystem	cost	LC	1.5 TeV $^{+}$	15 TeV $^{+}$	VLMC	VLHC	mu-p
e^{+} e with 375 GeV SC linac	3.0	X	X	X	X	X	X
1 ! 4 MW proton driv er	0.3		X	X	X	X	X
muon ionization cooling channel	0.7		X	X	X		X
by-pass line around e^{+} e IP region	0.1		X	X	X	X	X
375 GeV muon turnaround and tunnel	0.1		X	X	X		X
1.5 TeV collider ring (existing tunnel)	0.3		X				
muon optical sto chastic cooling	0.5		(X)	X	X		X
200 km tunnel	1.0			X	X	X	X
low eld recirculators to Ebeam=10 TeV	0.5			X	X	X	X
20 TeV collider ring and tunnel	1.0			X			
recirculating rings for E beam = 10 ! 50 TeV	2.3				X	X	X
100 TeV $^{+}$ collider ring additions	0.7				X		X
pbar cooling and p source	0.3					X	X
175 TeV pbar-p collider ring	3.0					X	X
mu-p by-pass lines & IP	0.4						X
miscellaneous	0.8						

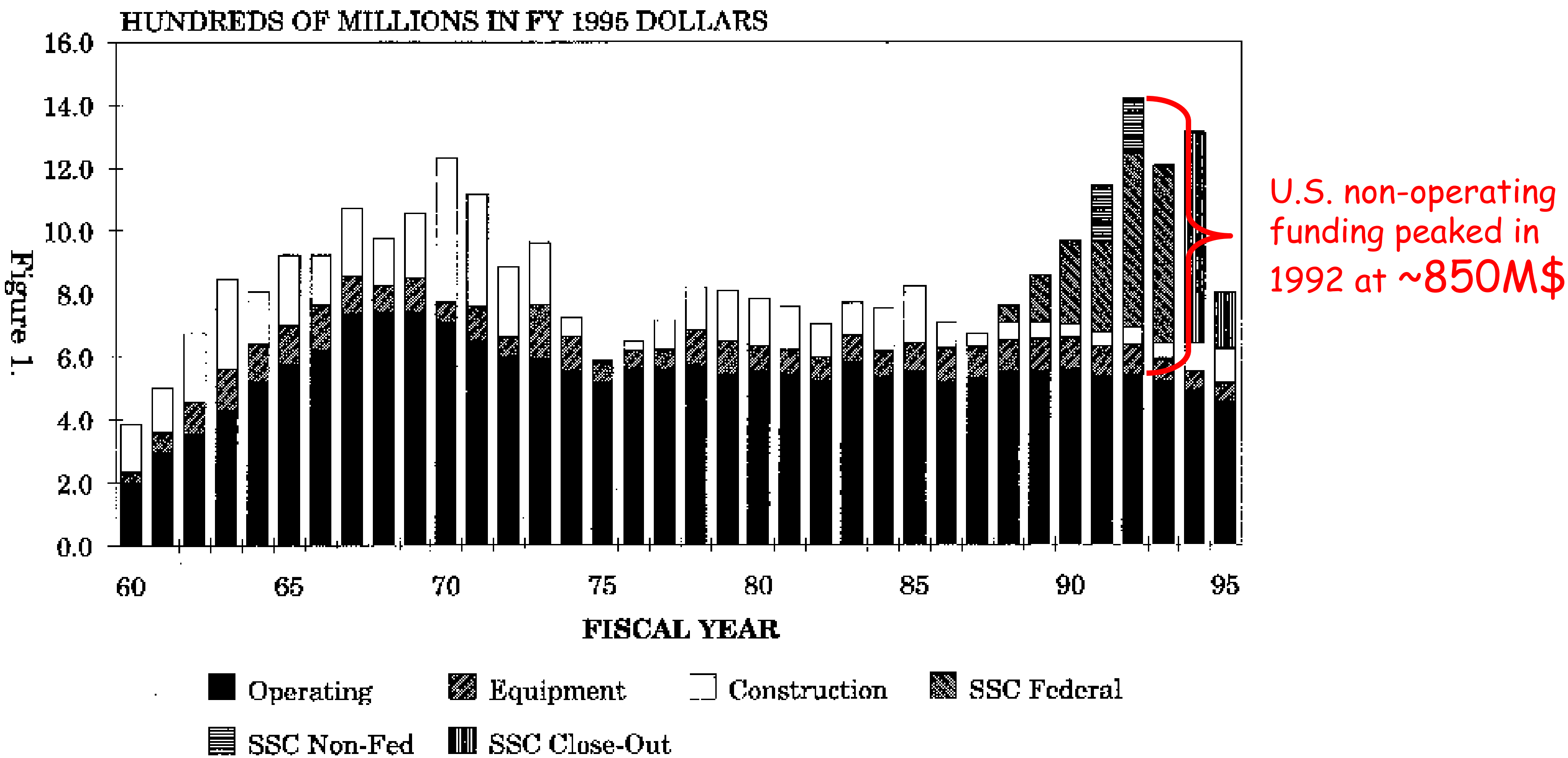
15.0 units

15 units/30 years = 0.5 units/year

1 unit ~ 1-2 B$ (“hand-waving” justifications in paper)

=> 0.5-1.0 B$/year for world-wide construction at energy frontier

U.S. HIGH ENERGY PHYSICS FUNDING (1960-1995)



Plot Source: HEPAP's Subpanel on Vision for the Future of High-Energy Physics, May 1994 ("Drell Report")

… so need consistent world-wide construction spending comparable with 1992 peak US-only spending.

This seems at least plausible!

SUMMARY

• muon colliders have magnificent HEP potential! Their development will greatly reinvigorate and strengthen the future of experimental HEP

• main challenges: beam cooling, neutrino radiation, cost management

• **"This is exciting! how can I help?"** Learn about them, think about them and talk about them; get involved where you think you can be most productive. E.g., critically important beam cooling simulations can provide ideal cross-over projects from other areas of HEP.